Keck Interferometer Observations

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Outline

- Overview of Keck Interferometer and current status
- NASA YSO observing programs
- T Tauri stars

- Other IR interferometry results at this meeting
  - Monnier – YSOs with closure phase talk (Monday)
  - Hinz – Herbigs with nulling talk (Monday)
  - Lopez - VLTI talk (next)
  - Patience poster – YSOs with KI
  - Eisner poster – YSOs with KI
  - Lui poster – Herbigs with nulling on MMT

The Keck Interferometer

- The Keck Interferometer is a NASA-funded project developed jointly by the Jet Propulsion Laboratory (instrument development), the W.M. Keck Observatory (instrument operations and development) and the Michelson Science Center (science operations and support)
- The interferometer combines the two 10-m Keck telescopes

Key Technical Features

- Michelson combination between the two 10-m Kecks
  - Keck-Keck baseline: 85 m (5 milliarcsecond fringe spacing at 2 μm)
- Phasing with adaptive optics and fast tip/tilt correction
- Cophasing with fringe detection/tracking and active delay lines
  - Dual-star feeds at each telescope
- Back-end instruments
  - Two-way beam combiners at 1.5 - 2.4 μm for fringe tracking (cophasing), astrometry, and imaging
  - Two-way beam combiner at 2 - 5 μm for differential phase
  - Nulling combiner at 10 μm

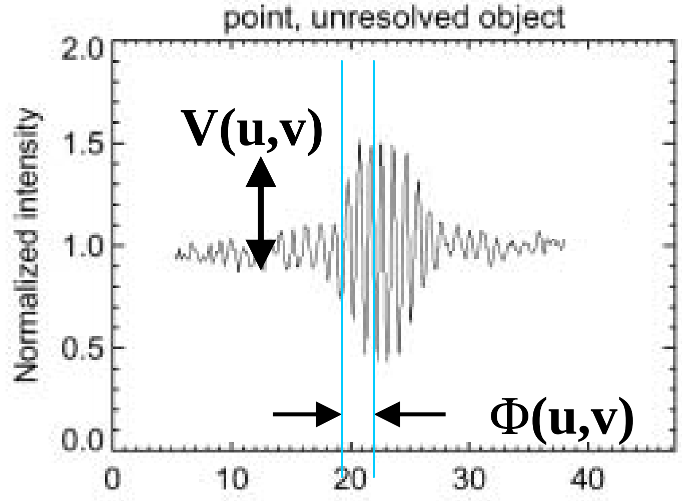
Basic principles (same as radio interferometry

$$\text{Brightness}(\alpha,\delta) \overset{F.T.}{\Leftrightarrow} \text{Visibility}(u,v)$$

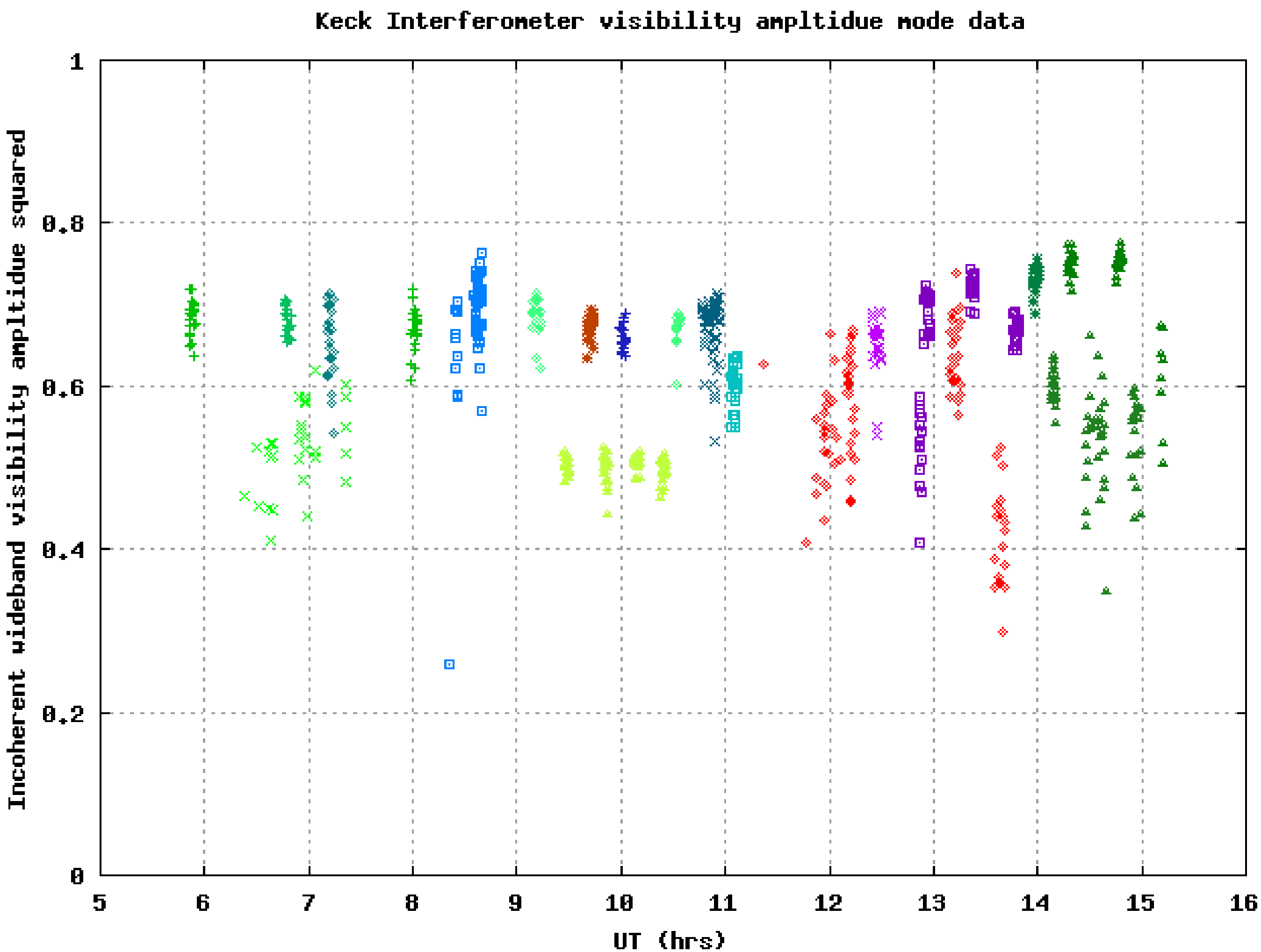
Sky coordinates

Spatial frequencies (baseline-source geometry)

- Visibility amplitude: fringe contrast
- Visibility phase: fringe phase
- But:
  - KI currently has only 1 baseline → very limited uv coverage
  - Fringe phase corrupted by atmosphere
- Model fitting to (a few) visibility amplitudes
- Works well for simple source morphologies and is the only way to probe these size scales in the infrared



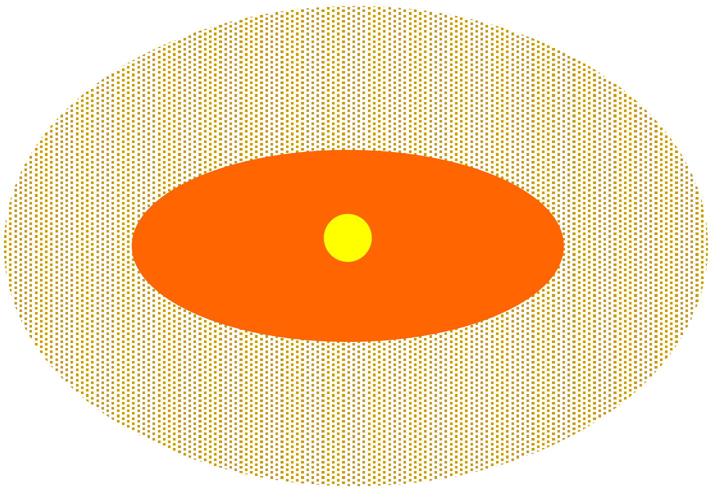
Example night of visibility data

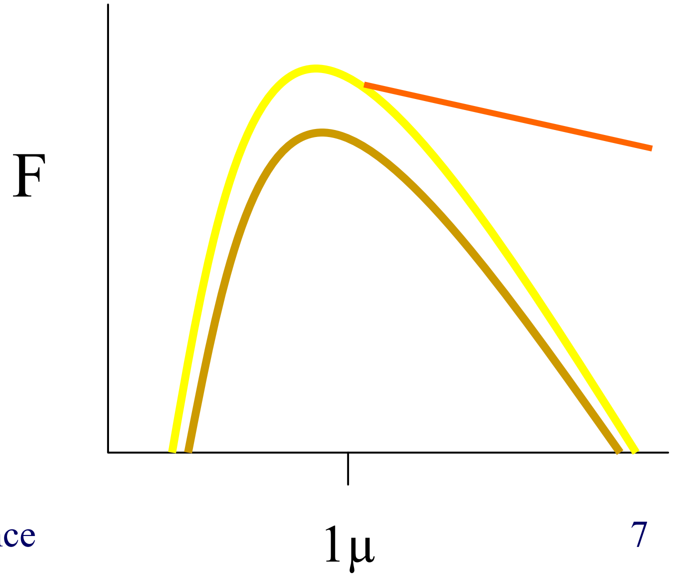


- Normalized, squared visibility amplitude
- Each point is 5 seconds of data
- One integration is 125 seconds of fringe data
- Alternate between science target and (unresolved) calibrator star

Young stellar objects with IR interferometry

- Stellar photosphere (unresolved at these distances d > 140 pc)
- Hot material in circumstellar disk
- Scattered light (generally incoherent contribution)





Previous Observations:

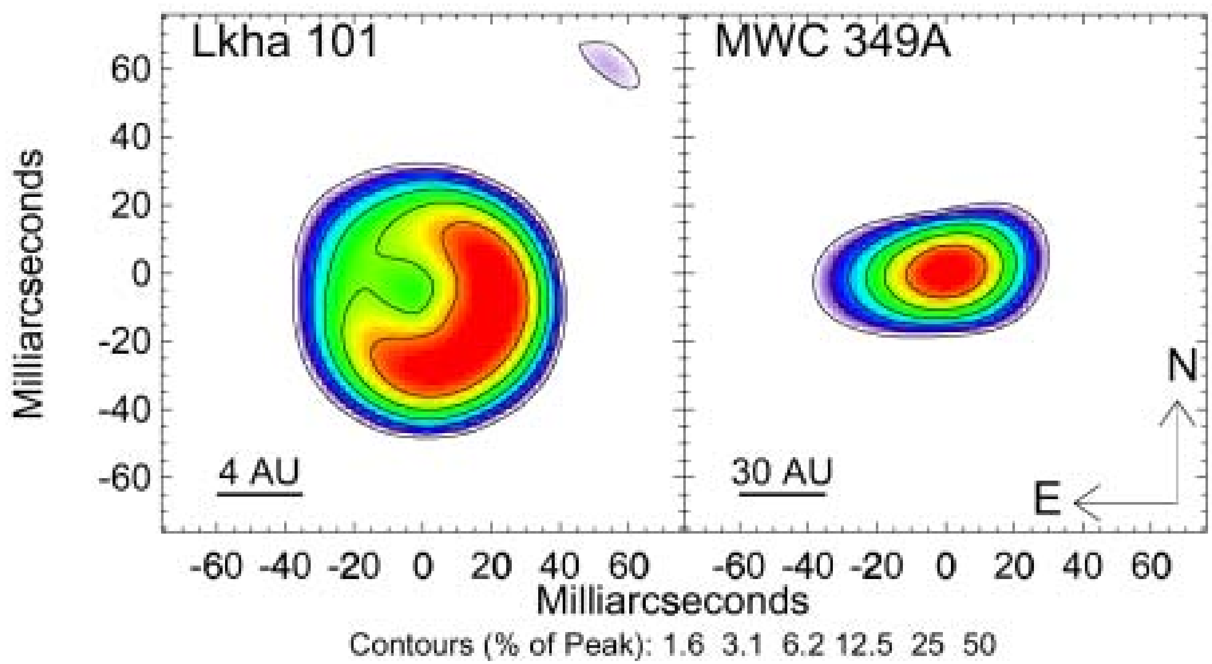
- Herbigs:
  - AB Aur (Millan-Gabet et al 1999, IOTA)
  - Survey of 15 Herbigs (Millan-Gabet et al 2001, IOTA)
  - 5 Herbigs (Eisner et al 2003, PTI)
  - General conclusions:
    - Late type Herbigs NOT consistent with flat accretion disks (too large, too few inclined source
    - Early types maybe more consistent with accretion disk (Eisner)
- T Tauris
  - 4 sources observed at PTI (Akeson et al 2000, 2004)
  - Also larger than predicted, but inclined disks observed
- FU Oris
  - FU Ori (Malbet et al 1998) consistent with accretion disk model

Implications for disk structure

- Data on many Herbigs more consistent with symmetric distribution than inclined disks
  - T Tauris and some Herbigs do have measured inclinations
- Observations do not agree with disk parameters determined using fits to spectral energy distributions
  - Measured inner disk radii *larger* than predictions
- Proposed model with inner disk radius set by dust sublimation temperature (Tuthill et al 2001, Natta et al 2001)
- Dullemond et al (2001) model based on Chiang and Goldreich (1997) flared disk with central hole
  - Inner rim of disk becomes vertically extended

Complimentary observations: Keck Aperture Masking

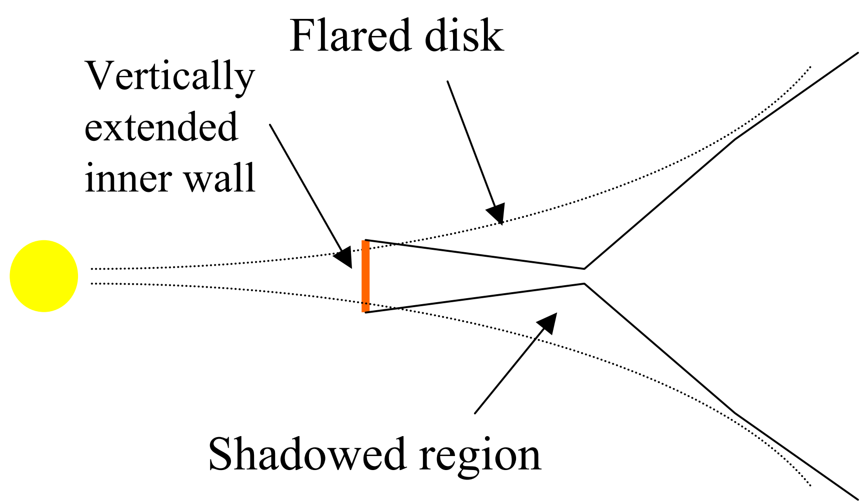
- Two extreme YSOs clearly resolved
- Direct disk evidence (inner cavity, elongated)
- Inner cavity size also “too large”
- Size consistent w. heating of opt thin dust

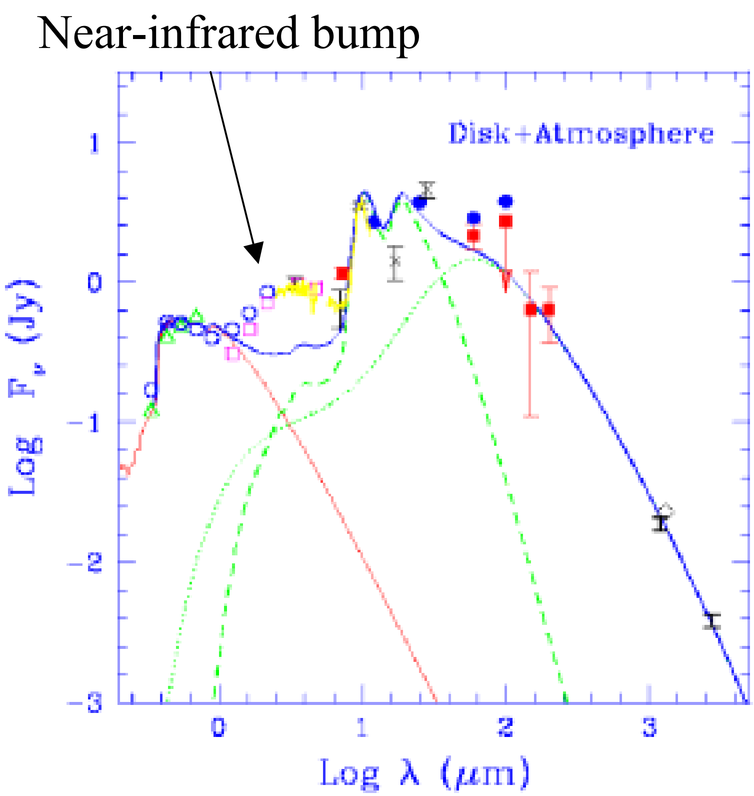


Tuthill, Monnier & Danchi 2001 Danchi, Tuthill & Monnier 2001

Disk model (Dullemond et al)

- Explains near-infrared feature in Herbig SEDs





KI NASA shared-risk YSO project

Star	Type	Resolved?
v1685Cyg	HAeBe B2	Yes
v1977Cyg	HAeBe B8	Yes
HD141569	HAeBe B9	No
HD58647	HAeBe B9	Yes
AS477	HAeBe A0	Yes
MWC275	HAeBe A1	Yes
HD150193	HAeBe A2	Yes
ww Vul	HAeBe A4	Yes
MWC758	HAeBe A7	Yes
HD142666	HAeBe A8	Yes
HD144432	HAeBe A9	Yes
ZCMa B	HAeBe	Yes

12 Herbigs

B2 $\rightarrow$ A9 sequence

DG Tau	T Tau G5	Yes
RW Aur	T Tau G5	Yes
LkCa 15	T Tau K5	Yes
BP Tau	T Tau K5	Yes
GM Aur	T Tau K5	Yes
V830 Tau	T Tau K7	Yes
DI Tau	T Tau M0	Yes

7 T Tauris

DG Tau results published: Colavita et al 2003, ApJL 592, 83

ZCMa A	FU Ori	Yes
v1057Cyg	FU Ori	Yes
v1515Cyg	FU Ori	Yes

3 FU Oris

T Tauris: internal team led by Akeson
Herbigs/FU Oris: shared-risk team led by Monnier
Massive Herbigs: shared-risk team led by Danchi

What can a single-baseline measurement tell us? Measure sizes of emission components in inner disk

- Must quantify stellar and extended contributions
  - Generally easy for Herbigs (IR excess dominates)
  - Harder for T Tauri's (variability)
  - FU Ori emission disk-dominated at these wavelengths
  - For the KI field-of-view (50 milliarcsec) observational constraints of extended emission are rare (significant source of uncertainty)
- Methods
  - SED fitting (difficult to find contemporaneous optical and infrared photometry, issues with variability)
  - Infrared veiling via spectroscopy (ideal but relatively few objects have been published)

Preliminary results for T Tauri objects

- Use KI observations to test disk model with inner disk radius set by dust sublimation temperature (Tuthill et al 2001, Natta et al 2001, Dullemond et al)
- Given the luminosity, the dust sublimation radius can be calculated for a given dust sublimation temperature

$$R_{dust} = \frac{1}{2}\sqrt{Q}\left(\frac{T_{star}}{T_{dust}}\right)^2 R_{star}$$

    - No backwarming of grains
- Two component model (except DG Tau)
    - Unresolved star (photospheric contribution preliminary for T Tauri's)
    - Circumstellar disk
        - K band contribution dominated by inner edge – use a ring geometry to represent

T Tauri sample

- KI

Note: not enough data to constrain inclinations – used face-on models

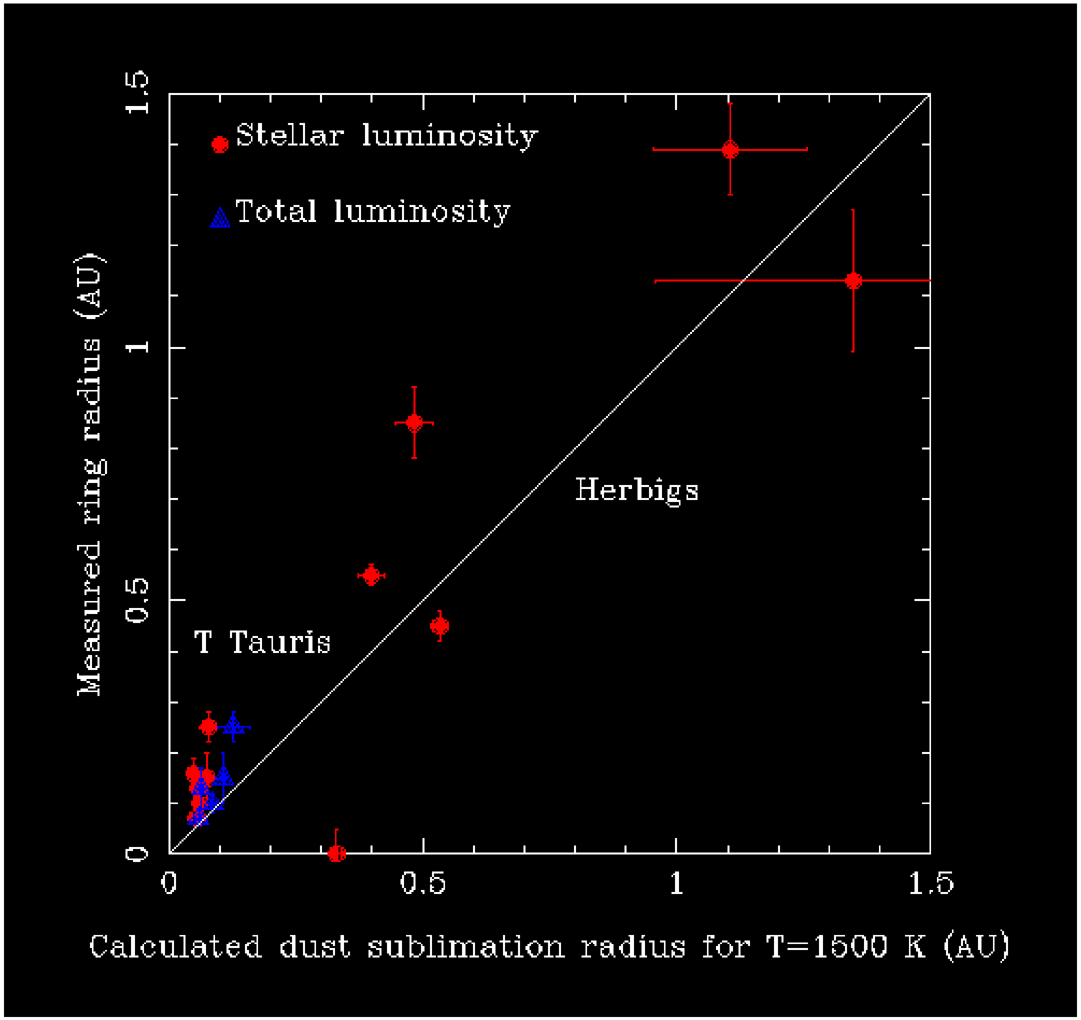
	Spectral type	K band excess flux (%)	K-L excess (mag)	Fit ring radius (AU)
DG Tau	G5	60-80 (20 scattering)	1.63	0.12 - 0.16
RW Aur	G5	73	1.07	0.25
BP Tau	K5	45	0.46	0.10
GM Aur	K5	19	0.22	0.13
LkCa 15	K5	68	0.46	0.07
V830 Tau	K7	0 – 15	0	0.16
DI Tau	M0	0 - 2	0.06	V^2 < excess

- PTI

Inclined model fits

	Spectral type	K band excess flux (%)	K-L excess (mag)	Fit ring radius (AU)
SU Aur	G2	44	0.69	0.18
RY Tau	K1	71	1.21	0.19
DR Tau	K7	80	1.36	0.078

Measured vs. predicted size (T Tauris and Herbigs)



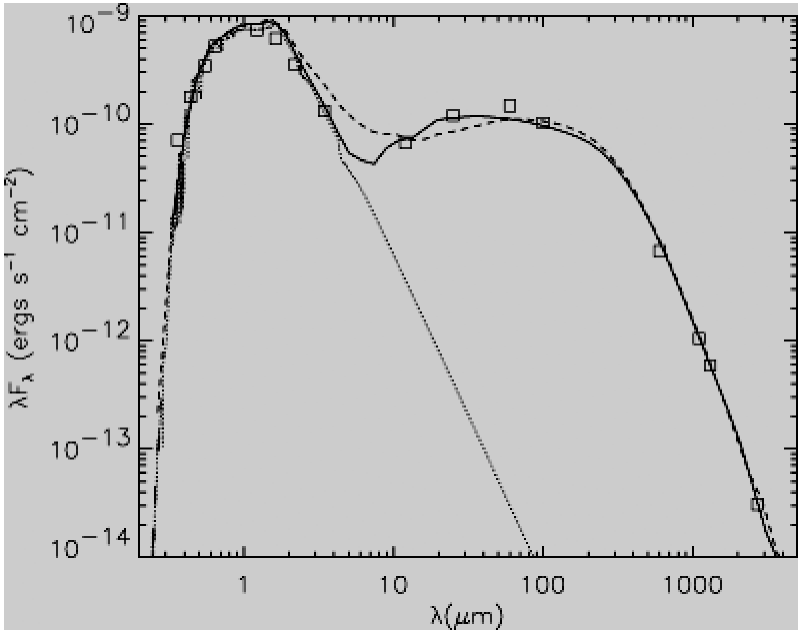
Calculated size from both stellar and total luminosity

- Face-on models (could underestimate size if inclinations are high)
- If extended component is large, these sizes are overestimates

But remember FOV is 50 mas

GM Aur

- Classical T Tauri star
- SED feature – proposed disk gap at 2.5 AU, possibly caused by an orbiting planet
  - This radius is outside the range of KI size sensitivity
  - Predicted astrometric signature is 0.1 milliarsec with a 4 year period → detectable by proposed outriggers or SIM
- KI data inner dust disk radius in the middle of sample (0.13 AU)



Rice et al (2003) model (dashed) line with R_{in}=0.06 AU and planet at 2.5 AU

V830 Tau (aka HBC 405)

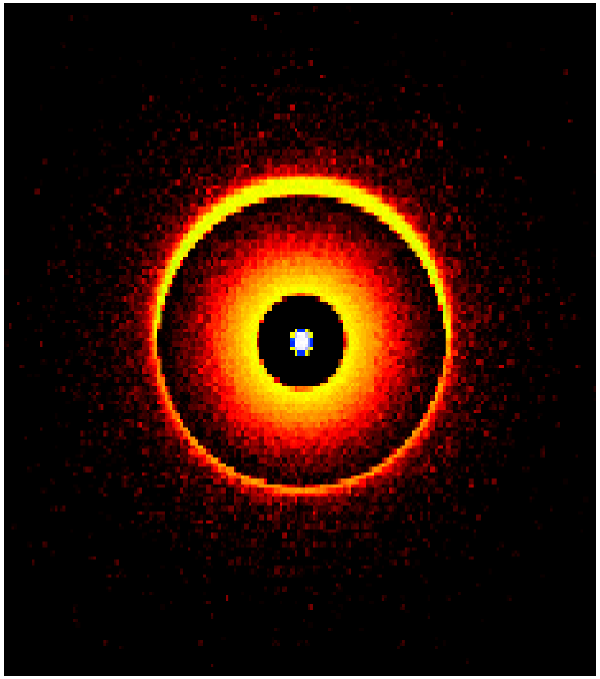
- Weak-line classification (Hα = 3.0 Å)
- Excess in SED at mid-IR wavelengths, but in near-IR estimates vary from 0 to 0.18 mags for ΔK
- KI data is resolved
  - If K excess is 0%, resolved visibility could be due to companion (but no RV signature seen by Sartoretti et al) within 50 mas
  - If K excess is ~15%, the inner disk is 0.16 AU (no scattering)
    - Much larger than predicted from stellar luminosity and accretion rate is low (< 10^{-8} M_{solar} /yr)
- Visibilities on another PMS X-ray source with no IR excess, HD2832798, are unresolved (as expected for photosphere only)

LkCa 15 (aka HBC 419)

- Border-line weak/classical (Hα = 13 Å) with very low accretion $2 * 10^{-9}\ M_{solar}/yr$
- But has large CO disk (450 AU) with Keplerian motions (Qi et al 2003; see also Kessler et al 2003) and Mdisk = 0.01 from long wavelength observations
- Small IR excess
  - KI data suggests small dust radii
  - With low accretion rate, the inner dust radius decreases significantly

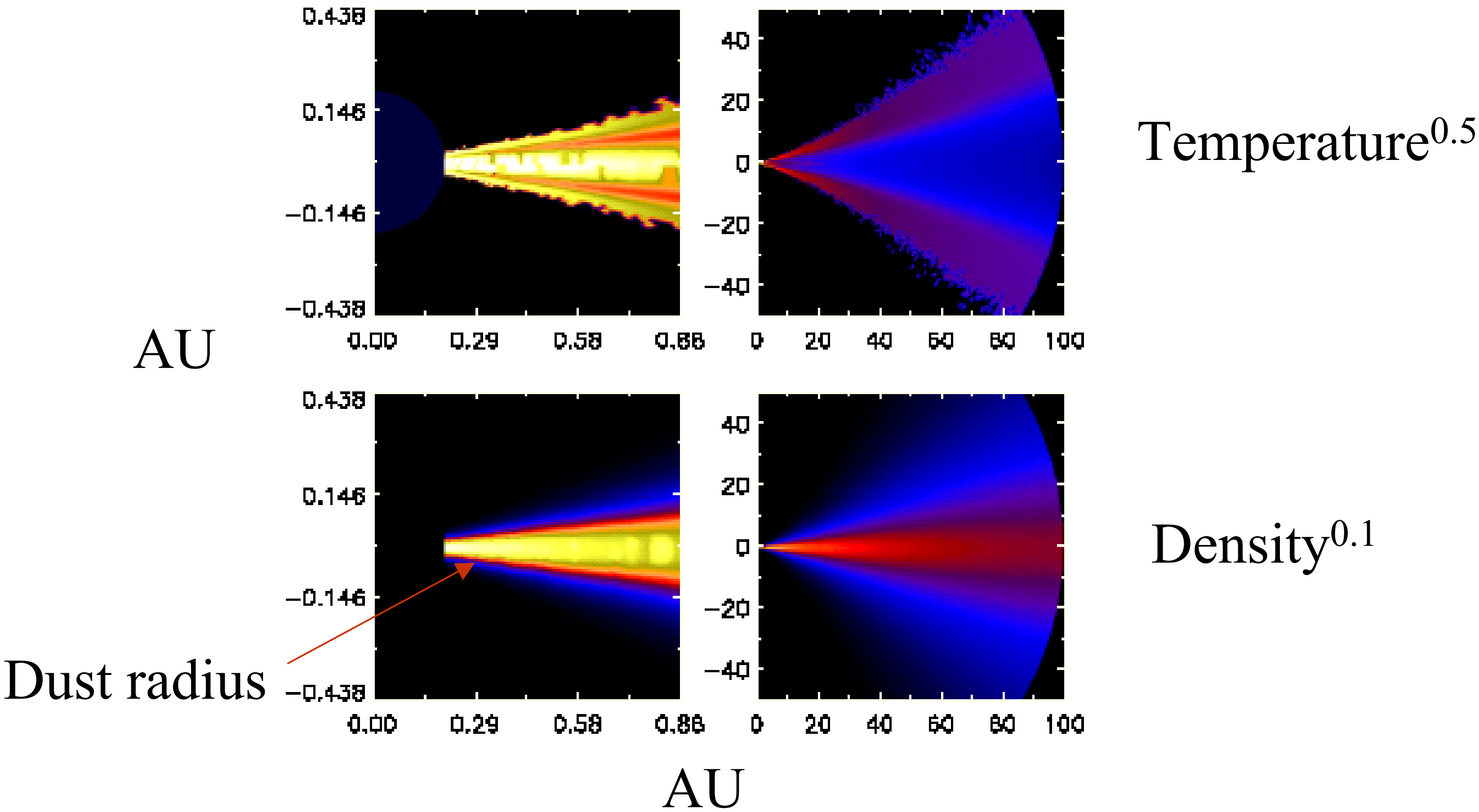
Detailed disk models

- Collaboration with K. Wood and C. Walker to model T Tauri SEDs and IR interferometry data
  - Directly model with "extended" emission (scales larger than a few milliarcseconds
- Monte Carlo models: include disk accretion, accretion onto the star and scattering
  - Components: central star, gas and dust disk: dust dissipated at 1600 K, smooth density profile
  - Gas inner radius set at corotation radius
    - Warm CO inner radii observed by Najita et al, Carr et al, Brittain et al
- For sources with large dust radii, the gas emission is significant at 2 μm
- For the PTI sources, the contribution from emission extended to the interferometer is less than 10% at K



K band image, 1 AU across

Temperature and density distributions

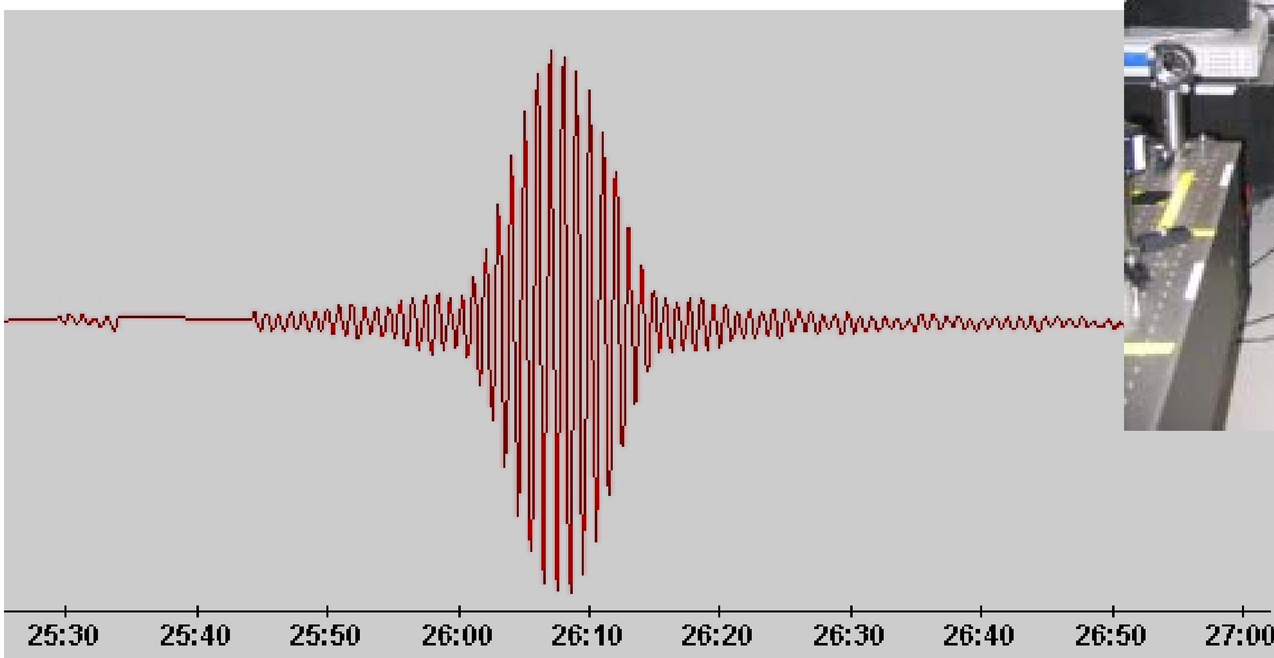


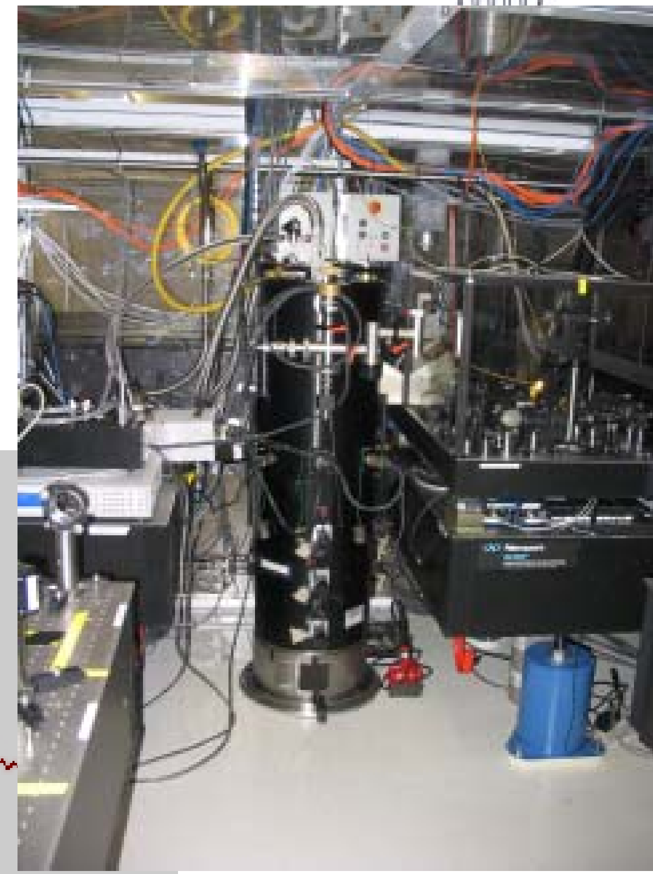
Future prospects

- Next generation of infrared interferometers now starting to produce scientific results: KI, VLTI, CHARA etc
- Imaging
  - IOTA closure phase results presented at this meeting (Monnier)
  - Planned capability at other facilities
- Other observing modes applicable
  - Nulling
  - Astrometry (companions and planets)
- Long term → TPF-I

KI nuller

- First 10 µm observations Aug 6-8
- First nulling observations Sept



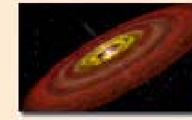


Conclusions

- The Keck Interferometer visibility amplitude mode is operational and available for proposals from the Keck user community
- Infrared interferometers now have enough sensitivity to observe "normal" classical and weak-line T Tauri stars
  - Need good photometry and/or IF spectroscopy to measure stellar contribution, variability is also an issue
  - For these stars, the inner dust radii range from 0.05 to 0.3 AU
    - Well outside the magnetic corotation radius
    - Roughly consistent with inner dust radii at the dust destruction point
      - Scatter is toward larger radii than predicted, but…
      - Need to assess extended contribution
      - Gas emission may be significant for some sources

From Disks to Planets: New Observations, Models and Theories



From Disks to Planets: New Observations, Models and Theories

March 7-10, 2005
Pasadena

First Announcement

To receive further announcements please email:
disks05@ipac.caltech.edu

http://msc.caltech.edu/conferences/2005/disks05/index.html

Topical sessions

- Global disk physics, chemistry and evolution
- New results from spatial interferometers: optical through radio
- First results from the Spitzer Space Telescope
- Disk imaging from the ground and space
- High resolution spectroscopy across the spectrum
- The inner 1 AU: observations and theory
- Initial conditions for planet formation
- Global properties of exo-planets

Location - Sheraton Pasadena Hotel

Area Maps
Accommodations
Weather

Transportation
Restaurants